Lower hybrid counter-current drive experiment in JET

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V. Basiuk[1], M. Goniche[1], J.F.Artaud[1], A.Ekedahl[1], F.Imbeaux[1], J.Mailloux[2], D.Mazon[1], Y.Peysson[1]

[1]*Association Euratom-CEA, CEA/DSM/DRFC, CEA/Cadarache,*
F-13108 St. Paul-lez-Durance, France
[2]*Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire, UK*

Abstract: Lower hybrid current drive has been demonstrated to be an efficient tool to modify the current profile in order to access to high energy confinement regimes. Counter-current drive could be an alternative scenario provided the current drive efficiency is not too small when fast electrons flow in the opposite way to the DC electric field.

By reversing the toroidal field (Bt=-3.1T) and the plasma current (Ip=-1.45MA), counter current drive with lower hybrid waves has been investigated for the first time in JET. The experiments were carried out at low plasma density ($\overline{n_e}$ =1.0 x10^{19}m^{-3} , $n_e(0)$=1.6 x 10^{19}m^{-3}) with 2.9MW of lower hybrid power.

The CRONOS code[1], which couples the diffusion equations to a 2-D equilibrium code, has been used to estimate the RF driven current. Runs indicate that loop voltage and internal inductance are best simulated with a current drive efficiency of –1.0 x 10^{19} A.W^{-1}.m^{-2} with a peaked central LH power deposition deduced from DELPHINE[2]. This efficiency is indeed very close to the one found for co-LHCD at similar plasma current and density. Current profile evolves from a hollow profile (with a minimum at r/a ~0) and a maximum at r/a~0.4-0.5) to a rather flat profile (up to r/a=0.3).

I) Introduction

Hollow current profiles are helpful to provide enhancement in the energy confinement for plasmas of tokamak. These regimes can been achieved using central counter current drive tools. During the session devoted to reversed toroidal field and plasma current at JET, first experiments were done using the LH wave in counter current with a power level around 3 MW. The density was rather low ($\overline{n_e}$ =1.0 x10^{19}m^{-3}) and a high value of central electron temperature was observed (above 8 keV). A stationary state was achieved after 8 seconds, with a loop voltage of 0.4 V. The plasma current was about 1.5 MA and the toroidal field 3.5 T. We will focus our discussion on three discharges :

- shot 59671, in counter current
- shot 57326, in co current
- shot 59670, ohmic shot

Far all these discharges, electron temperature profiles are deduced from ECE and Thomson scattering diagnostics. There are no ion temperature, charge effective and current profiles measurement. Analysis of these shots are made with the CRONOS package[1], using the code DELPHINE[2] to estimate the LH current profile. The DELPHINE[2] code includes the effect of the electric field in its calculation of the LH current. Correction of the hot conductivity[3] due to the high value of the electric field is taken into account. The consistency of the simulations is insured with comparison of : the experimental loop voltage (V_l), self inductance (l_i), poloidal beta (β_p) and reconstruction of Faraday's angles.

II) Data analysis

Table 1 shows a brief description of main plasma parameters of the shots. The internal fit procedure of the CRONOS[1] package is used to assess the electron temperature and density profiles which allows combining spatial and temporal information and different diagnostics.

Figure 1 shows that the co and counter current shots achieved the same total confinement energy time, around 0.2 s, just above the L-mode scaling[4]. The small evolution of the confinement time is not investigated, as it is rather difficult to fit the electron temperature as shown in figure 2. Because of fast electron emission, the ECE measurement can only be used when the normalized radius x is in the range 0-0.3 and there is not a fairly agreement between Thomson scattering (Lidar) and ECE : even in the core, the ECE measurement is found to be ~20% higher than the Thomson scattering measurement and best trade-off was assumed for the electron temperature profile. Z_{eff} profiles are deduced from the central line-integrated Z_{eff} measurement assuming a $1/n_e$ radial scaling. The ion temperature is assumed to be proportional to the electron temperature, with a factor 1/3 (due to the fact that LH waves heat electrons).

The CRONOS code[1] is used in its interpretative mode (the current diffusion equation is solved, coupled to a 2 D equilibrium) to simulate these shots. A first run is made using the code DELPHINE[2], which is a ray tracing coupled to a relativistic 2D Fokker Planck solver. It includes the effect of the electric field. The code lasts around 10 minutes and is processed every 50 ms for the LH current sources (the total simulation of one shot of 12 seconds takes 2 days CPU). It used the full equilibrium calculated by HELENA[5] in a self consistent manner with the current diffusion equation.

For the counter current shot (#59671), the LH power deposition is predicted on-axis during the first 2 s of the simulation. Then, starting from 47 s, the LH power deposition moves outwards and a bump of counter-current drive appears at $\rho \sim 0.7$ (ρ being the normalised toroidal flux coordinate). This results in a fast peaking of the current profile, as shown by the increase of internal inductance li (fig. 4).

As this phenomenon is not observed in the experimental data, we suppressed this parasitic bump, keeping the total LH current constant for the rest of the simulations. With this correction, which give an on axis and relatively broad LH current (typical width 0.4), the figure 4 shows that the slope of the l_i evolution is well reproduced.

The discrepancy on the exact value of l_i is assigned to the initial value of the current profile. In a CRONOS simulation, the first equilibrium has to be guessed, giving a current, total pressure profile and the plasma separatrix (in [R,Z] coordinate). A small modification of the initial current (figure 4, which is deduced from Faraday angle inversion) is a way to increase the central current and to start with a greater l_i closer to the experimental one, allows to simulate quite well (within the error bar) the l_i.

The first conclusion of this analysis is that the on axis counter-current drive profile deduced from DELPHINE in the first 2 seconds of the simulation (figure 3) is validated by the various reconstructions of experimental data. As a CRONOS run gives access to a 2D equilibrium (every 10 ms, consistent with the current diffusion equation), it is possible to reconstruct the Faraday angles. The result of this reconstruction is shown in figure 5 where the agreement is good although two chords show a systematic difference greater than the error bar of the measurements (0.2 °). The density profile is also compatible with the interferometry chords which are reconstructed using the same procedure.

The plasma current density profile evolves from an hollow profile to a broad profile where a steady state is almost reached at the end of the shot (figure 9 a).During this evolution, the central temperature (~8 keV) remains quite constant.

For the co-current experiment, (shot 57326), which has plasma parameters close to the counter-current shot (see table 1), a similar analysis is made. The deposition profile deduced from DELPHINE is unambiguously off axis with a maximum at $\rho=0.5$ (figure 6) and the loop voltage and l_i evolution deduced from CRONOS are not far from the experimental values (figure 7b, 7d). The pressure seems to be over estimated (figure 7c). This shot has a similar confinement time with a broader electron temperature and a much lower central temperature (table 1).

III) LH efficiency

In the previous paragraph, the resistive current diffusion has been calculated using the "cold conductivity", i.e. assuming a Maxwellian electron distribution function. Nevertheless, the presence of tail of suprathermal electrons driven by the LH waves changes the conductivity. In this paragraph, we quantify this modification of the conductivity by a simple analytical method.

In the presence of a dc electric field, neglecting the bootstrap current, the total plasma current may be written as $J_{tot}= J_{OH} + J_{LH} + \sigma_1 E + \sigma_2 E^2 + \ldots$ where J_{OH} is the ohmic heating (OH) current that results in the absence of RF power, J_{rf} is the RF current that results in the absence of a dc electric field and $\sigma_1 E + \sigma_2 E^2 \ldots$ are additional currents that result when both LH power and DC field are present. Introducing the plasma conductivity σ_{sp} (Spitzer conductivity), $J_{OH} = \sigma_{sp} E$. If we take into account only the first cross-term, where σ_1 is called the hot conductivity, the total current can be expressed by the following formula :

$$J_{tot}= \sigma_{sp} E + J_{LH} + \langle E.B \rangle \sigma_{hot}/B$$

A simple approach was developed in CRONOS based on analytical formula[3], using a normalised LH current profile (deduced from DELPHINE) and a prescribed LH efficiency (η) to calculate the total LH current (I_{LH})

$$I_{LH} = \eta \frac{P_{LH}}{R_0 \bar{n}}$$

and the additional current using the following formula for (σ_{hot}).

$$\sigma_{hot} = \frac{\sqrt{\pi}}{2} \frac{P_{lh}}{n_e^2} \frac{(5+Z_{eff})^2}{(3+Z_{eff})} \eta^2,$$

where P_{lh} is the LH injected power (MW), n_e the electron density profile (m^{-3}), Z_{eff} the charge effective profile, R_0 the major radius and $\bar{n} = \frac{n_l}{2a}$ with a the minor radius and n_l the central line-integrated density.

The plasma conductivity, calculated by the neoclassical module NCLASS[6] is also modified above a threshold (E_{max}) on the parallel electric field[7].

$$E_{\max} = \frac{e^3 \ln(\lambda) n_e(x=1)}{4\pi\varepsilon_0^2 m_e c^2}\left[\langle Z_{eff} \rangle + 2\right]$$

Values of the parallel electric field profile ($E_{//}$) greater than this threshold are replaced by the threshold. Then the resistivity is modified :

$$\sigma = \frac{E_{//}}{E_{neo}} \sigma_{neo}$$

For the shots analyzed, the threshold (0.07 V/m with the plasma parameters of the counter current shot 59761) is well above the observed electric field (~0.02 V/m).

The best reconstruction, for the counter current shot, of both the loop voltage and the self inductance is obtained for a given efficiency η = -1×10^{19} A W^{-1} m^{-2} as shown in figure 8, where $\Delta V_l = \left\langle V_l^{cronos} \right\rangle - \left\langle V_l^{\exp} \right\rangle$ and $\Delta li = \left\langle li^{cronos} \right\rangle - \left\langle li^{\exp} \right\rangle$ are computed. The effect of the mean value of Z_{eff} is also studied.

An increase of Z_{eff} improved the V_l reconstruction but not the l_i one. Reducing the electron temperature at the edge degraded both the l_i and V_l reconstruction. The LH efficiency for the counter current shot is close to that of the co-current shot (η = 0.8×10^{19} A W^{-1} m^{-2}) with a similar study to the counter current one, finding the best reconstruction of the loop voltage and the self inductance (figure 9). Figure 10 shows the evolution of the total current of the two shots (co and counter).

IV) Kinetic approach

Even if the kinetic code DKE[8] is not coupled to CRONOS, a first approach has been made to test the validity of the CRONOS simulation using the stand alone version of DKE, with electron, density and electric profiles from CRONOS for the counter current case.

The main point addressed by the simulation is to test if the resistivity deduced from NCLASS and so the parallel electric field must be corrected in the central region of the plasma where the LH current density is high (1MA / m^2 at the plasma center). Figure 11 shows the 2D distribution function of the electron population in the $v_{//}$, $v_{\perp}$ space. One can see the effect of the pitch angle scattering which makes some of the fast electrons generated by the LH wave (in counter current) contribute to co current drive. With these plasma parameters, the code DKE needs a higher central electric field (by at least a factor 10, up to 0.2 V/m at the center) to achieve a positive and flat total current profile in the central area (x=0-0.3 in normalized radius).

Preliminary conclusions of these studies is that the parallel electric field in CRONOS is significantly under estimated in the central region due to a lower conductivity, arising from the LH heating and namely the presence of a non thermal tail. This electric field should be then very high in this region to totally balance the counter LH current (negative source) and to achieve a flat but positive profile in the central region. This high value of the central electric field could be responsible of the high central electron temperature observed which does not depend on the current profile (it remains constant during all the evolution of the current profile).

This calculation stresses the necessity to perform fully self consistent kinetic calculation of the LH power absorption and the Ohmic electric field, for evaluating correctly the effective conductivity that must be used in the resistive current diffusion process.

V) Conclusions and future

Although the large DC electric field LH is expected to reduce the current drive efficiency when the current is driven in the opposite direction to the plasma current, this analysis, using a simple model for the effect of the electric field on the LH current drive, shows that indeed counter current drive has a comparable efficiency when compared to the co-current case. The much higher electron temperature (factor of 2) where LH deposition occurs may explain, at least partially, this high efficiency. Nevertheless current profiles differ significantly. In the co-current drive case, the plasma current density profile evolves from very peaked to less peaked profile whereas for the counter-current drive the profile is clearly hollow for 5 seconds relaxing to a rather peaked profile. It should be stressed, however, that the timing of LH power is different for the two cases (in the case of co-current, the LH power is only 1 MW in the ramp-up phase) and further experiments would be necessary. The central counter-current drive is a feature which can be used in the future to access high confinement regimes.

Self consistent simulations of such discharge where a high parallel electric field coexists with the fast electron population will be done in 2005 when the new LH module will be coupled to CRONOS with a more rigorous calculation of the resistivity and the parallel electric field

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Pulse number	59670	57326	59671
configuration	Ohmic shot	Co CD	Counter CD
I_p (MA)	1.5	1.3	-1.45
$n_e(0)$ 10^{19} m^{-3}	1.65	1.5	1.6
$T_e(0)$ keV	3.0	5.7	7.8
α_{Te}	3.3	2.5	3.3
β_p	0.1	0.2	0.2
l_i	1	1.15	1.2
τ *(s)*	0.3	0.2	0.2
LH efficiency		0.8 10^{19} A W^{-1} m^{-2}	1 10^{19} A W^{-1} m^{-2}

Table 1 : main plasma parameters of the shots. The peaking factor α is defined by fitting a profile with the following form, $(1-x^2)^\alpha$, where x is the normalized toroidal coordinate. The total time confinement LH efficiency are also given.

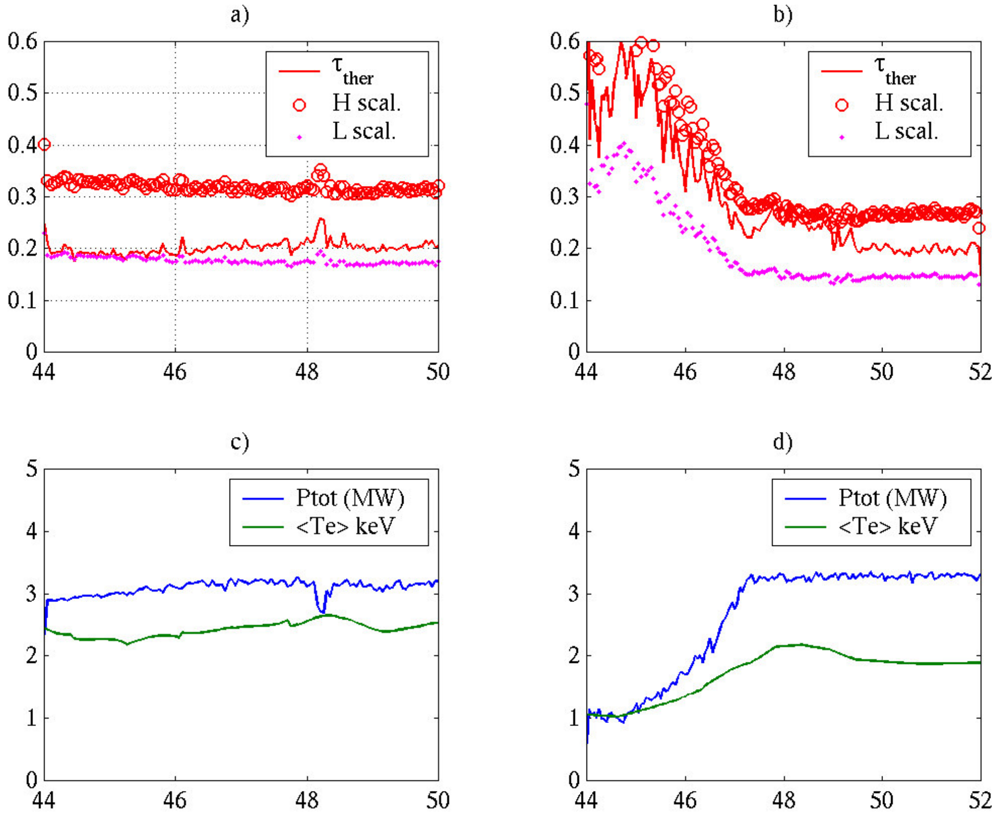

Figure 1: a) and b) confinement time for the shot 59671(counter current case) and 57326 resp (co current case)., compared to an L-mode scaling law (H97) and H-mode scaling law (IPB98y2), c) and d) the total injected power and the averaged electron temperature for #59671 and 57326 respectively shots

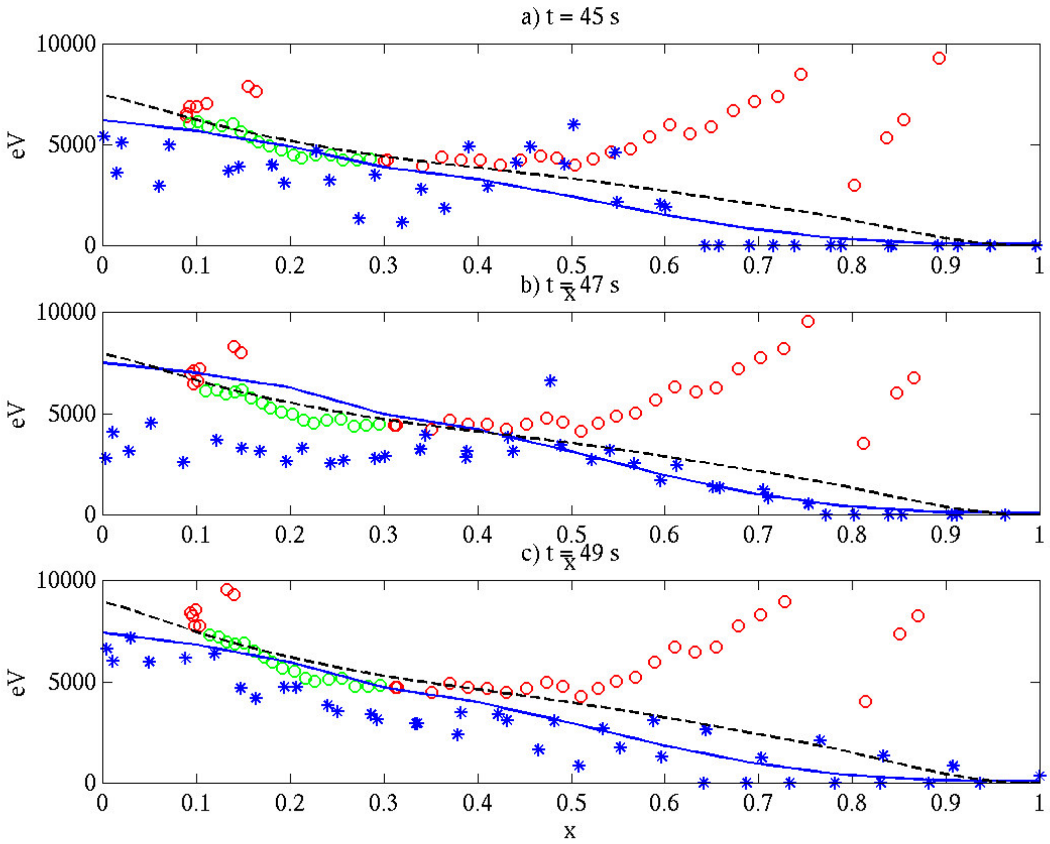

Figure 2: Electron profiles at three different time. open circle : data from KK3 diagnostic (ECE), stars : data from Lidar diagnostic (Thomson scattering), dotted line : fit using only KK3, full line : fit using both KK3 and Lidar

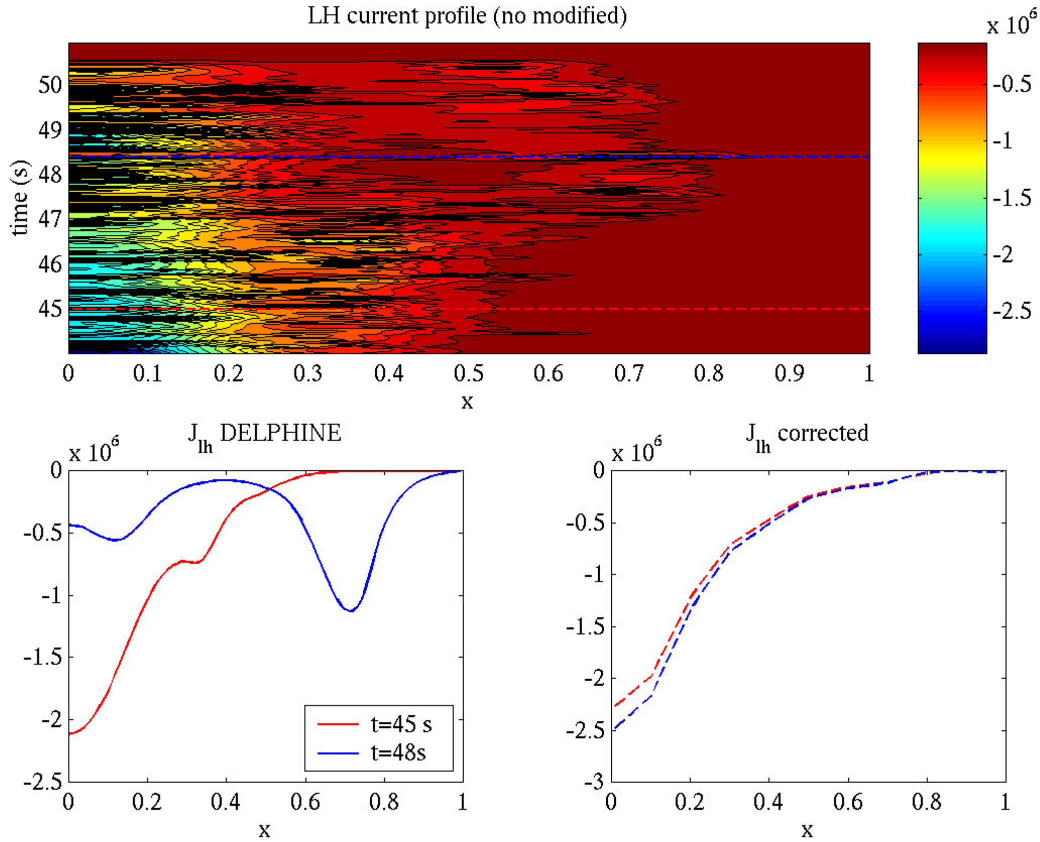

Figure 3: Evolution of the LH current profile calculated by DELPHINE for the counter current shot #59671. The correction of the LH profile is made conserving the total LH driven current.

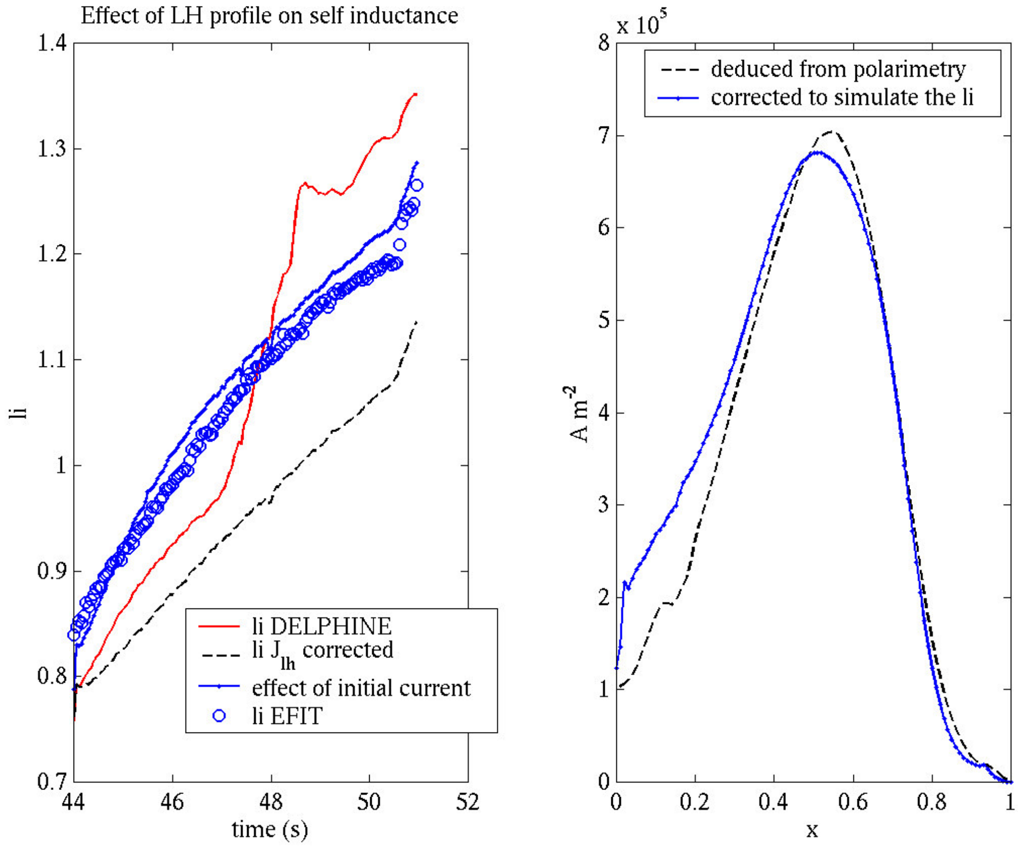

Figure 4: #59671, counter current shot. Effect of the LH profile on the self inductance. The left figure shows also the effect of the initial profile current in the CRONOS code where the two different current profiles are shown in the right picture.

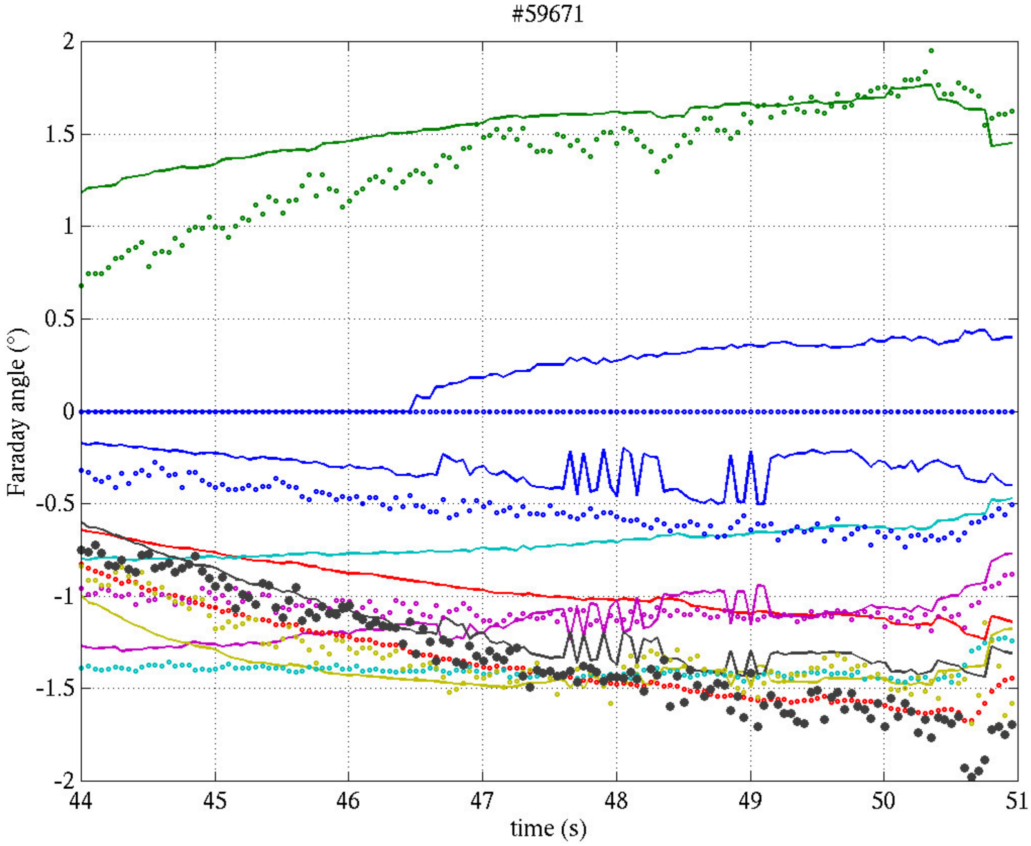

Figure 5: Reconstruction of Faraday's angles with CRONOS (full line : CRONOS reconstruction)for the shot #59671 (counter current case)

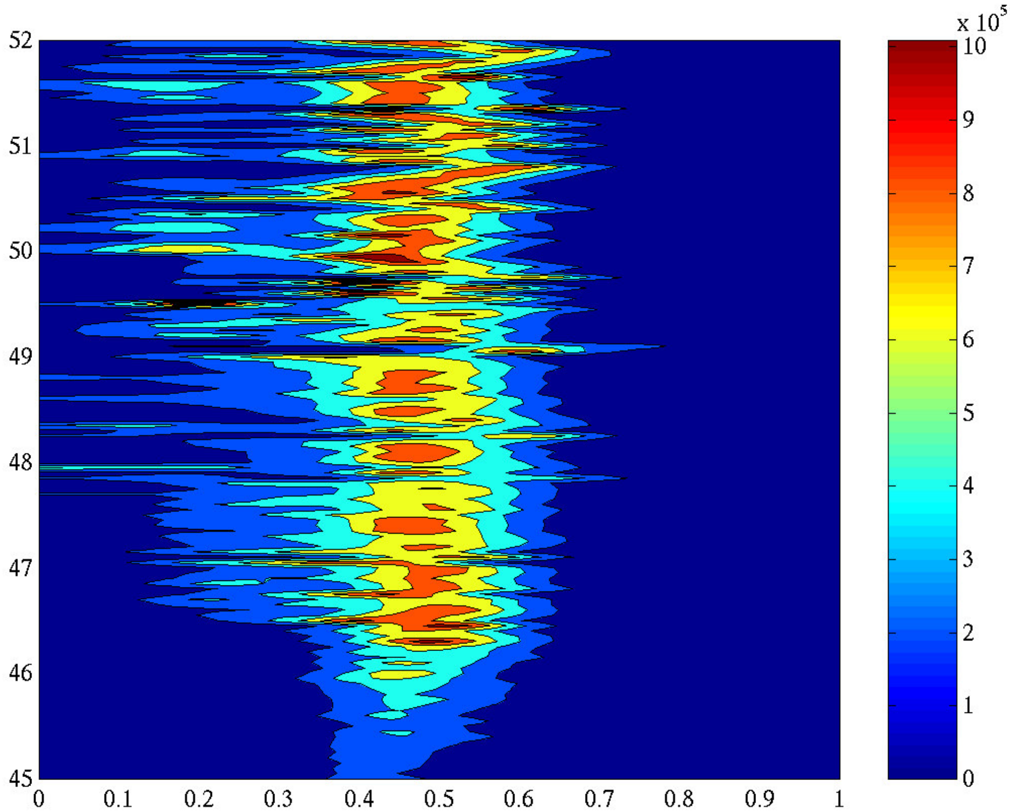

Figure 6: contour plot of the absolute value of the LH current profile (A m^{-2})calculated by DELPHINE for the co current case (shot #57326). In the simulation the correct negative sign is included

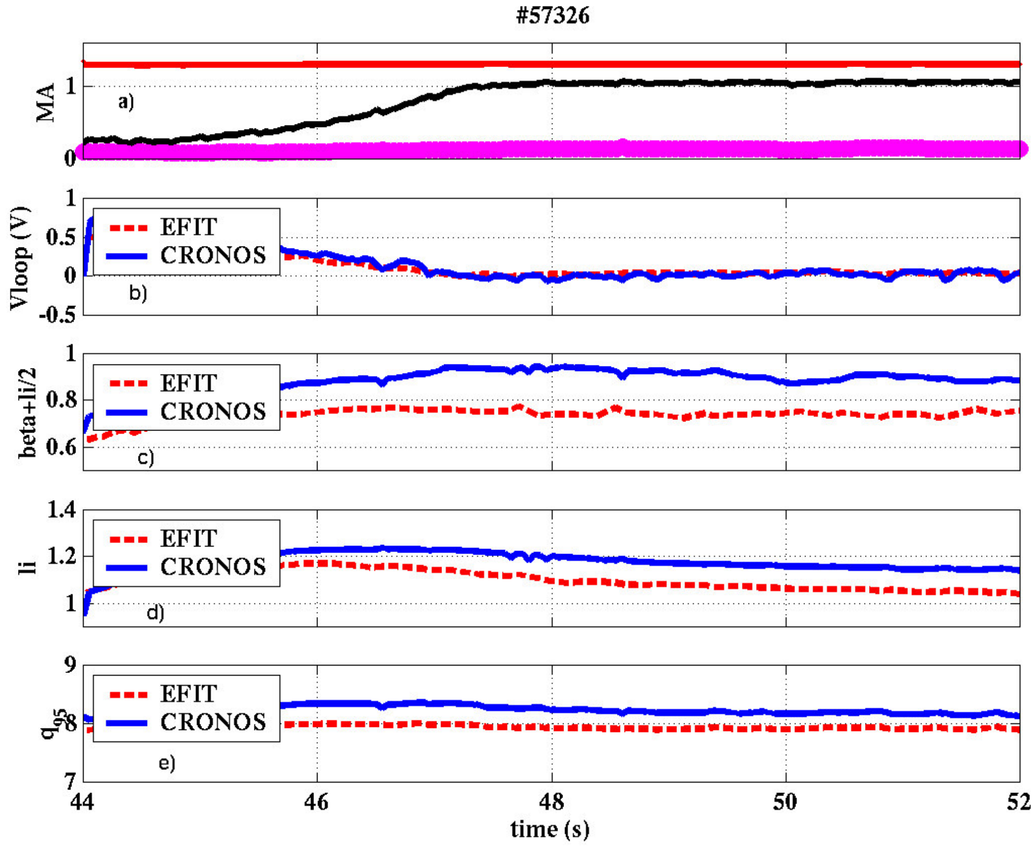

Figure 7: Simulation of the co current shot (#57326) with CRONOS. a) presents the plasma current (in dot, it is the one deduced from CRONOS) in red, in black the non inductive current and in magenta the bootstrap current, b) shows the loop voltage evolution (CRONOS is full line) c) the Shafranov evolution, d) the self inductance evolution and e) the toroidal safety factor at x=0.95.

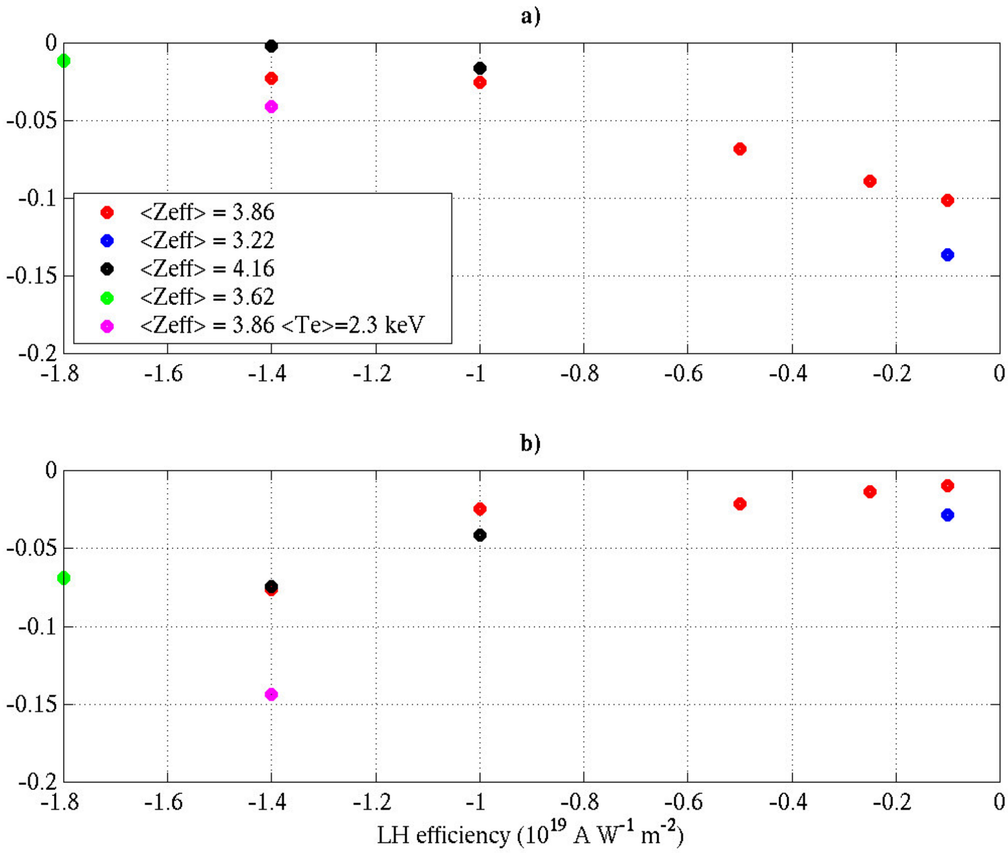

Figure 8 : counter current case, shot #59671, cronos simulation results.a) effect of LH efficiency on the loop voltage (V_l) reconstruction. The time average reconstruction of V_l between t=44s and t=49s of CRONOS is compared to the experimental one b) same comparison with the self inductance. Effect of the charge effective (Z_{eff}) and the Te profile is also shown (all the simulation are made with $<T_e>$ = 2.4 keV except one where the profile was flatten at the edge ($<T_e>$ = 2.3 keV).

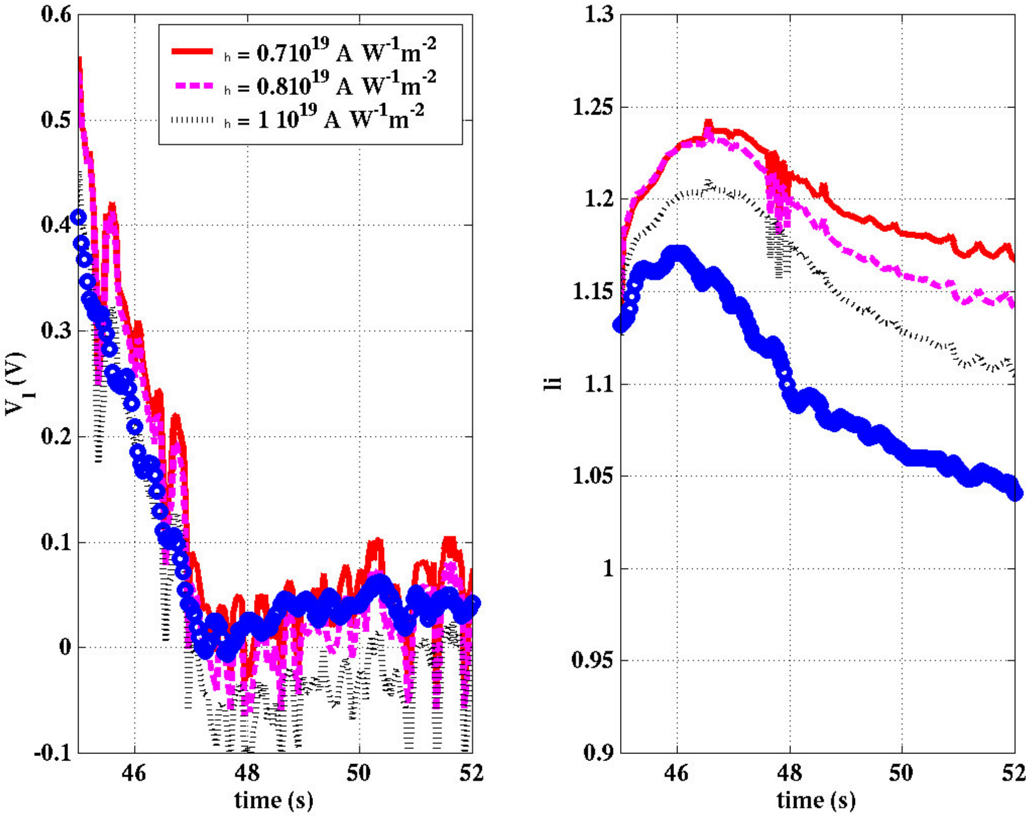

Figure 9: co current case (shot #57326). Reconstruction of the loop voltage and the self inductance, varying the LH efficiency with a LH current profile deduced from a DELPHINE run.

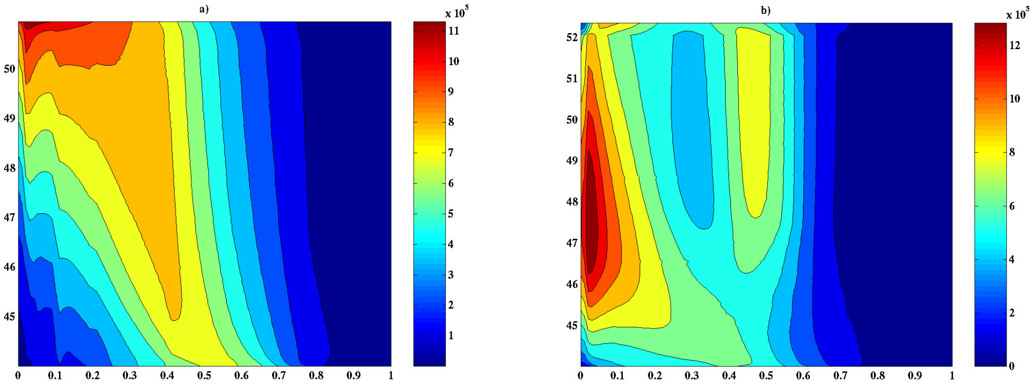

Figure 10 : Contour plot of the total current profile(in A m^{-2}) deduced from CRONOS a) for the counter current case #59671 b) for the co current case #57326

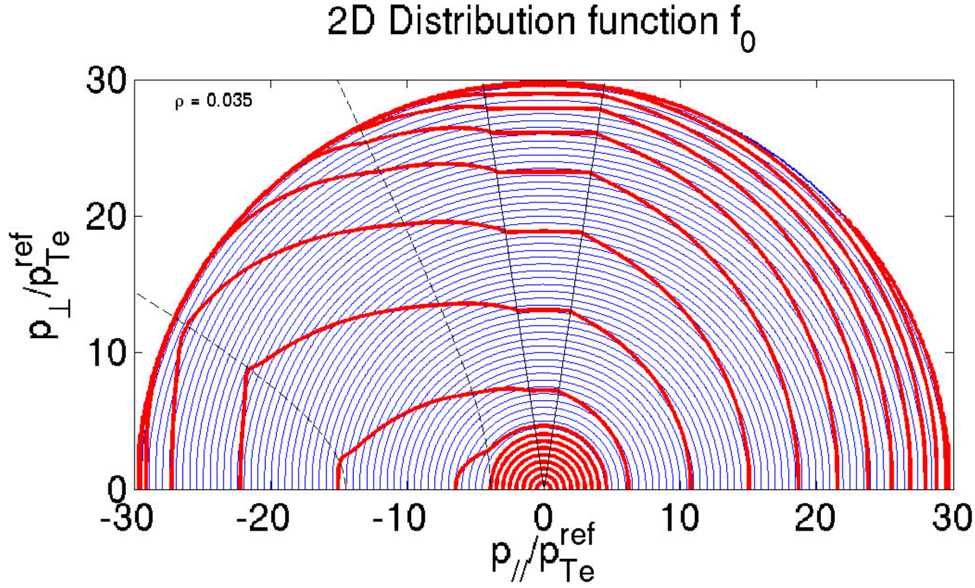

Figure 11 : electron distribution for the counter current shot (#59671) at t=50 s. The negative part shows the effect of the lower hybrid wave on the fast electron population. Pitch angle scattering supplied the positive part (allows co current from fast electrons)